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LANDING SIMULATION EXPERIMENTS: FIXED VERSUS MOVING BASE AND PURELY VISUAL APPROACH

FLIGHT SYSTEMS INTEGRATION AND ANALYSIS BRANCH
FLIGHT CONTROL DIVISION

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Some effects of visual and motion cues on simulated aircraft landing performances were investigated. Three primary objectives were posed: 1. Does the motion system affect landing performance? 2. Can the simulator be landed without the use of cockpit instruments? 3. Can the simulator be landed with conventional aircraft values of sink rate at touchdown? The experiments revealed that (1) the limited motion system had minor effects upon landing performance, (2) the simulator can be landed successfully without use of the cock-

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pit instruments, and (3) the simulator can be landed with a mean sink rate of 2 ft/sec if the pilot retards the throttles after touchdown. Changing the aircraft dynamic response has a greater effect upon the pilot's landing performance than turning off the motion system.

FOREWORD

This report presents the results of some simulation experiments conducted in-house by the Flight Systems Integration and Analysis Branch, Flight Control Division during September and October 1975. The purpose of the experiments was to investigate the performance of the multicrew cab simulator, so as to be better able to characterize its capabilities for planning future simulations, and to provide a data base for evaluating simulator improvements. The work was performed under project Number 1986, Task Number 01, Work Unit Number 06.

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LIST OF SYMBOLS AND ABBREVIATIONS

ADI	Attitude Director Indicator.
F	A distribution used in statistical tests.
g	The acceleration due to gravity (32.2 ft/sec).
GPIP	Glide path intercept point.
$\dot{h}$	Altitude rate (ft/sec).
HSI	Horizontal Situation Indicator
ILS	Instrument Landing System.
p	Roll rate in body axes (deg/sec).
q	Pitch rate in body axes (deg/sec).
r	Yaw rate in body axes (deg/sec).
RMI	Radio Magnetic Indicator.
s	Laplace transform operator.
SCAS	Stability and Control Augmentation System.
t	A distribution used in statistical tests.
x	Along runway position coordinate with origin at GPIP (feet).
$\dot{x}$	Along runway velocity (ft/sec).
y	Cross runway position coordinate (feet).
$\dot{y}$	Cross runway velocity (ft/sec).
VASI	Visual Approach System Indicator.
z	Vertical position coordinate (feet).
$\dot{z}$	Sink rate (ft/sec).
α	Angle of attack (deg).
β	Sideslip (deg).
Δ	Vertical deviation from a nominal three degree glide slope (feet).
θ	Pitch angle (deg).
σ_{u_g}, σ_{v_g} σ_{w_g} σ_{p_g} σ_{q_g} σ_{r_g}	- Standard deviations associated with turbulence model.
ϕ	Roll angle (deg).
ψ	Yaw angle (deg).

The x, y, z coordinate system used has x positive along the runway pointing away from the runway threshold, z positive down, and y completing a right handed coordinate system. The origin of coordinates is located at the GPIP.

SECTION I

INTRODUCTION

The simulation of aircraft approaches and landings has recently become important because of the low cost, safe, flexible opportunities it presents for aircrew training, pilot/aircraft system research and engineering, investigation of potential flight hazards, and accident investigations. Some examples of these possible applications are the use of flight simulators by the airlines and the United States Air Force in aircrew training, the use of simulators to investigate aircraft handling qualities and failure modes before the aircraft is built and flown, the use of simulations by the National Transportation Safety Board to determine probable cause of air carrier accidents, and the low visibility landing program conducted for the Federal Aviation Administration by the Flight Dynamics Laboratory (1), (2).

For these applications to be feasible, it is necessary to relate simulation results and performance to actual results and performance for the appropriate task. It is also necessary to know that the pilot does not significantly change his behavior in going from an actual aircraft to a simulation of that aircraft. If the pilot did significantly change his behavior in going from an actual aircraft to a simulator, it would be difficult to relate simulation results to the results obtained with the actual aircraft, and the simulation results could be very misleading.

The pilot's behavior is strongly influenced by his environment. Since a simulator cannot fully reproduce the environment of actual flying, the simulator must be designed to supply to the pilot those visual, motion, and other cues which are used by the pilot in the particular flying task being simulated. These cues must have sufficient fidelity so that the pilot does not change his behavior pattern for the task being simulated.

Little data is presently available relating simulator performance with actual flight performance, and it is difficult to specify what level of fidelity for what cues is necessary to have a good simulation of a

[illegible] In an effort to identify cues which significantly affect [illegible] landings, the experiments in this report were conducted to [illegible] the effect upon a pilot's landing performance of removing certain cues.

The cues presented in modern simulators are visual cues, which try to reproduce what the pilot would see; sound cues, which try to reproduce what he would hear; motion cues, which try to reproduce the mechanical motion felt by his body; and feel system cues, which attempt to present the correct forces and gradients for moving the simulated aircraft's controls. It should be noted that the visual cues and motion cues both contribute to the pilot's sensing of motion.

Experience to date indicates that it is difficult to simulate landing an aircraft in such a way that the simulated touchdown performance is comparable to the performance achieved by a pilot in a real aircraft (1), (2), (3), (4), (5), (6), (7). The statistic most commonly reported about landing simulations is the mean sink rate at touchdown, and the mean sink rate is generally significantly higher in the simulation that it would be for an actual aircraft. When other data is reported, it also has shown differences between the simulation and comparable data from actual aircraft. Table 1 presents statistics on the sink rate at touchdown for possibly 14 different simulations. Certain of these simulations are only minor variations of one another, and there may be some overlap in the simulations listed. However, at least four different aircraft (VC-10, COMET 3B, DC-8, and C-135B) were simulated, both fixed base (no motion) and moving base (roll, pitch, heave) simulations are represented, and five different types of visual displays (two types of TV display, perspective display, projected display, and computer generated display) were used. Despite this variety of simulation techniques, the simulations of Table 1 all had sink rate statistics which were larger than would be expected of an actual aircraft.

Experimental investigations of the differences between simulator landing performance and aircraft landing performance have not determined any specific single factor which contributes most of the difference

TABLE 1

STATISTICS ON SINK RATE AT TOUCHDOWN

SOURCE	SIMULATION RESULTS MEAN ± STANDARD DEVIATION	FLIGHT RESULTS MEAN ± STANDARD DEVIATION
1. ARMSTRONG 1968		
CRANE (TV, MOTION)		
SIMULATOR PILOTS	8.5 FT/SEC MEAN	1.5 FT/SEC MEAN
AIRLINE PILOTS	16.0 FT/SEC MEAN	1.5 FT/SEC MEAN
RAE BEDFORD (TV, MOTION, VC 10)	6.8 FT/SEC ± 3.6 FT/SEC	
BLEU SIMULATOR (PERSPECTIVE, FIXED BASE, COMET 3B)	4.2 FT/SEC ± 2.6 FT/SEC	1.0 FT/SEC ± .8 FT/SEC
2. BROWN 1968 (PERSPECTIVE, FIXED BASE, COMET 3B)		
VISUAL SEG. < 1300 FT	6.2 FT/SEC ± 3.4 FT/SEC	
VISUAL SEG. > 1300 FT	6.6 FT/SEC ± 2.6 FT/SEC	
RAE BEDFORD		1.0 FT/SEC ± .7 FT/SEC
CIVIL AIRLINE USAGE		1.6 FT/SEC ± .4 FT/SEC
3. BROWN 1970 (PERSPECTIVE, FIXED BASE, COMET 3B)		
RAF 1966	7.8 FT/SEC ± 3.3 FT/SEC	
RAF 1967	4.2 FT/SEC ± 2.8 FT/SEC	
RAF 1968	3.8 FT/SEC ± 1.3 FT/SEC	
CIVIL PILOTS, 1968	4.6 FT/SEC ± 2.2 FT/SEC	
TYPICAL FLIGHT VALUES		2.2 FT/SEC ± 1.0 FT/SEC

TABLE 1 (CONTINUED)

STATISTICS ON SINK RATE AT TOUCHDOWN CONTINUED

4. ARMSTRONG & MUSKER 1970 (PROJECTED, FIXED BASE)			
100 BEA COMMERCIAL PILOTS		9.2 FT/SEC ± 2.8 FT/SEC	
5. PALMER & CRONN			
(FIXED BASE, LC 8) COMPUTER GEN. DISPLAY	AFTER 10 RUNS	4.66 FT/SEC ± 1.87 FT/SEC	
	AFTER 50 RUNS	2.53 FT/SEC ± 1.25 FT/SEC	
TV DISPLAY (BRAY)	AFTER 10 RUNS	5.9 FT/SEC ± 2 FT/SEC	
	AFTER 30 RUNS	3.9 FT/SEC ± 1.3 FT/SEC	
AVERAGE FLIGHT PERFORMANCE			1 TO 2 FT/SEC
6. FAA LOVISIM 1974 (TV, MOTION, C-135B)			
PHASE I (PILOT MODELING)		13.0 FT/SEC ± 4.2 FT/SEC	
PHASE II (PILOT MODELING)		6.5 FT/SEC ± 2.4 FT/SEC	
PHASE II (SURVEY)		7.12 FT/SEC ± 3.54 FT/SEC	
T.O. 1C-135A-101			NOMINAL 2 FT/SEC

between simulator and aircraft performance (3). A landing is defined to be the aircraft touches down on the runway, neither too short, too long, too far left, or too far right, that it can be kept on the runway after touchdown, and that it did not touch down at an excessive rate. Since no single specific factor has been related to the difference between simulator and aircraft performance, and since attaining maximum realism of cues in a simulator is limited by necessary physical limitations (such as the amount of travel allowed in motion drive systems) and the economic law of diminishing returns, the objective of attaining realistic pilot behavior in landing simulations must be obtained by a careful, broadly based effort.

One approach to attaining realistic performance has been to thoroughly familiarize the pilot with the simulation, giving him several hours of simulation time or 40 or 50 simulated landings before the experiment is started and data are collected. However, it has been objected that this approach results in a pilot who flies the simulator like a "pin ball machine", with behavior considerably different from that which he would exhibit in an aircraft. The "pin ball machine" effect is defined to be the pilot flying the instruments of the simulator to take advantage of the relatively disturbance free repeatable task to improve his performance, instead of using the same behavior he would use in an aircraft.

A second approach would be to analyze what cues are used by the pilot to accomplish the landing task, and then concentrate on providing accurately only the minimum cues necessary. The difficulty with this approach is that no clear consensus exists as to what cues are used during the landing task, and the relative importance of the various cues is a subject of considerable debate.

The main cues are what the pilot sees (visual cues), what he hears (sound cues), and what his body feels (mechanical motion cues and control feel). The mechanical motion cues arise from mechanical motion of the pilot and aircraft exciting the vestibular system, or resulting in pressure on the skin, and contribute to the pilot's sensing of motion.

However, the visual cues provide the main contribution to the pilot's sensing of motion, and it is difficult to predict _a priori_ for a given task whether mechanical cues will be significant to the pilot for that task.

The experiments reported on in this report provide information useful to either of the above approaches to aircraft landing simulations. For the first approach, information was obtained on possible learning effects and how many simulation runs would result in stabilized touchdown sink rate performance. On some of these runs, the instruments were frozen at their initial trim conditions, and the pilot's performance and behavior studied for this situation. Freezing the instruments prevented a possible "pin ball effect". For the second approach, the effect of the available mechanical limited motion cues upon touchdown performance was studied; and the question, "Are the visual display and limited mechanical motion cues sufficient to simulate a landing?", was investigated.

The remainder of this report is organized as follows: Section II describes the physical equipment used in the simulation and the pilot's task. Section III describes the objectives of the simulation experiments, how these experiments were conducted, what data was collected, and background information about the subject pilot. Section IV discusses the results of the simulation, organized by objective. At the end of Section IV is a brief summary of the experimental results. Finally, Section V presents the conclusions of the experiments and recommendations for further work.

SECTION II

DESCRIPTION OF THE SYSTEM

A. Pilot's Task

The objectives of the simulation experiments of this report were to investigate some effects of visual and motion cues upon simulated aircraft landing performance. Therefore, the pilot's task in the simulation was to execute a conventional visual flight rules (VFR) approach and landing, depending mainly upon the visual display for the information required for flight path guidance. The pilot was asked to use the primary flight controls, visual information, and what instrument information was displayed on that run to accomplish a safe landing.

All approaches were conducted under simulated daylight conditions with unlimited visibility. Each experimental run began from trimmed flight conditions at 750 feet altitude on a three degree glide slope. The pilot then took over and using only visual information flew a nominally three degree glide slope approach to the runway, flared, and touched the aircraft down. He was not provided with glide path indication. The run was then terminated after touchdown occurred.

The pilot was briefed to perform what he considered a normal landing for the airfield. He was not briefed to attempt to minimize sink rate or to land at a specific point on the runway. The runway size was 11,500 feet by 200 feet.

B. Aircraft Simulated

The aircraft used for this simulation was a four engine jet transport aircraft of approximately 180,000 pounds gross weight. The aircraft had conventional aileron, elevator, rudder, and throttle controls. In addition, through the use of spoilers, the aircraft had a direct lift control. The aircraft also had blown flaps which resulted in considerable powered lift. Longitudinal control in this simulation

was accomplished through the use of the direct lift control and the pitch trim button, while lateral control was accomplished through use of the ailerons. In normal configuration, the aircraft had an extensive stability and control augmentation system (SCAS). Certain simulation runs were made with this system operating, and other runs were made with the bare airframe and no stability augmentation.

The controls the pilot used to fly the aircraft did not change between the SCAS on and SCAS off conditions. The SCAS system was a three axis system, feeding back pitch rate, pitch attitude, and bank angle in the pitch axis; roll rate and roll angle in the roll axis; and sideslip, yaw rate, roll angle, and lateral acceleration in the yaw axis. The SCAS damped and modified the basic aircraft responses to such an extent that the SCAS on and SCAS off conditions appeared to the pilot like two different aircraft. The SCAS on configuration represented an aircraft with good handling qualities, while the SCAS off configuration represented an aircraft with poorer handling qualities, especially in the lateral axis.

The instrument panel was organized in a [illegible]ntional manner. The flight instruments driven during the simulation were the attitude director indicator (ADI), horizontal situation indicator (HSI), airspeed indicator, rate-of-climb indicator, barometric pressure altimeter, radar altimeter, angle of attack indicator, g meter, Mach meter, elapsed time clock, and compass indicator (RMI). The engine instruments driven were the engine pressure ratio gauges, tachometers, exhaust gas temperature gauges, fuel flowmeters, and oil pressure gauges. Since the simulation was concerned with visual approach and landing, the pitch and roll command bars of the flight director were stowed and not driven. On certain of the simulation runs, which were for the purpose of determining if the simulation could be landing using only visual and motion cues, all cockpit instruments were frozen at their initial trim conditions. The airport VASI system was not on, and the pilot did not have raw ILS information.

C. Simulation Equipment

The aircraft mathematical model was programmed on the hybrid computer system located in the Flight Control Development Laboratory, Air Force Flight Dynamics Laboratory. The aircraft model was a six degree of freedom nonlinear model, and incorporated landing gear, the feel system, and the control system in addition to the aerodynamic model. The aircraft model used body axes and aerodynamic data for computing aerodynamic forces, and moments were stored in the digital part of the hybrid computer and used to determine the instantaneous flight conditions for use in the analog part of the hybrid computer.

The cockpit was a C-135 cockpit that had been modified for use as a research and development simulator. It was mounted upon a three degree of freedom motion base, with the degrees of freedom being pitch, roll, and heave. The limits of the cockpit motion were (9):

Vertical cockpit translation: ± 13 inches

Angular rotation in pitch: + 14°, -6°

Angular acceleration in roll: ± 9°/sec^2

Vertical acceleration: ± 0.8 g about 1 g

Initial angular acceleration in roll: 50 deg/sec^2

Initial angular acceleration in pitch: 50 deg/sec^2

Due to flow limitations in the hydraulic system, the acceleration limits were not attainable during all simulation runs. The flow limitations would result in a decreasing acceleration capability as run time increased or the amplitude of the commanded motion increased. No data is available on how the flow limitations affected this simulation.

The transfer functions from the aircraft states to the three hydraulic actuators on the motion base were:

$$\text{Left Actuator:} \quad 6 \frac{s}{s+.35} [.2\phi + .035p] + 3 \frac{s}{s+.25} [.6q - .856\dot{h}]$$

$$\text{Right Actuator:} \quad -6 \frac{s}{2+.35} [.2\phi + .035p] + 3 \frac{s}{s+.25} [.6q - .856\dot{h}]$$

$$\text{Rear Actuator:} \quad \frac{s}{s+.25} [3 (.6q - .856\dot{h}) + .17375\ \theta]$$

The pilot station is located three feet directly above a line connecting the left and right actuators. The rear actuator is located 87 inches to the rear of this line, on the cab centerline. The left and right actuators are located 46 inches to the left and right of the cab centerline (9).

Sound cues were generated to increase the realism of the simulation. The sound cues duplicated the sound of four turbojet engines, and were proportional to throttle position and airspeed.

Visual cues simulating real world changes in size and perspective with respect to aircraft motion were produced using a three dimensional illuminated terrain model and television camera-screen projection system. The television camera-screen projection system took the image of the terrain board and projected it onto a screen. The image on the screen was then presented to the pilot and copilot simultaneously by reflecting it in a curved parabolic mirror. The mirror is located six feet in front of the pilot and copilot stations. The field of view of the screen was 60 degrees diagonally. The view was large enough to present a realistic scene through the front windows, but there were no peripheral cues. During an approach, the pilot saw a rural terrain with an airport complex including strobe and approach lights. All simulation runs were daylight approaches. The VASI were turned off.

During the simulation runs, turbulence inputs were generated and inserted into the simulation. Turbulence inputs were used in this simulation so that the simulated aircraft dynamics would be disturbed, forcing the pilot to make control inputs, and preventing him from letting the initially trimmed aircraft land itself. The turbulence corresponded to light turbulence having the Dryden spectra of military specification 8785 (10). The turbulence inputs had typically:

$$\sigma_{u_g} = 2.50 \text{ ft/sec}$$

$$\sigma_{v_g} = 2.50 \text{ ft/sec}$$

$$\sigma_{w_g} = 1.65 \text{ ft/sec}$$

$$\sigma_{p_g} = .44 \text{ deg/sec}$$

$$\sigma_{q_g} = .33 \text{ deg/sec}$$

$$\sigma_{r_g} = .44 \text{ deg/sec}$$

SECTION III

DESCRIPTION OF THE EXPERIMENTS

A. Objectives

The objectives of the experiments described in this report were to answer the following three questions:

1. Does the motion system affect landing performances?

2. Can the simulator be landed without the use of the cockpit instruments?

3. Can the simulator be landed with conventional aircraft values of sink rate at touchdown?

These objectives were selected as being capable of being answered with the equipment and resources available, while at the same time being of interest with respect to the simulator landing problem. To directly attack comparing simulator landing performance with real aircraft landing performance would require data from an actual aircraft of the type being simulated, which was not available. However, by studying the effects of withholding certain cues in the simulator, it is possible to determine which cues significantly affect landing performance. Under the assumption that only a cue which significantly affected landing performance was important to the pilot, it might be possible to identify those cues where a small change in fidelity might seriously change the pilot's performance.

The definition of landing used in question 2 is that a landing consists of setting the aircraft down upon the runway surface, and keeping it there during rollout, while not touching down at excessive rates.

Question 1 was answered by conducting an experiment where motion was used half the time, and not used the other half of the time.

The results were then analyzed to see if motion was a significant factor. Question 2 was answered by conducting a series of approaches and landings with the cockpit instruments frozen at their initial trim condition, and the motion system on. These results were then compared with the first experiment's results for comparable cases. Question 3 was answered by keeping a chronological record of the touchdown sink rate of every simulated landing made with this aircraft by the subject pilot, including practice runs and runs made for subsequent experiments. This record was then examined for learning effects and changes in performance.

Only one pilot was used in this experiment, as enough simulation time was not available to duplicate the experiments with other pilots. It was felt that the pilot used should make enough runs to determine what was his average performance.

B. Experimental Designs

The experimental design used to answer Question 1 was a 2 x 2 x 10 factorial experiment (11) where the factors were:

1. Motion system on or motion system off (fixed base).

2. Stability and control augmentation system on or stability and control augmentation system off (bare airframe).

3. Replication (there were 10 replications).

Motion system on or off was selected as a factor as the objective of the experiment was to determine the effect of motion on landing performance. The SCAS on or SCAS off factor was selected because the aircraft had good handling qualities with the SCAS on, and poorer handling qualities with the SCAS off (flew like a different aircraft). It has been hypothesized that motion cues are not very important to the pilot of an aircraft with good handling qualities, but are important to the pilot of an aircraft with poor handling qualities. Collecting data for the two SCAS configurations allowed this possible interaction

to be investigated. The replications were selected so as to indicate whether any effects observed were repeatable.

Before the experiment began, the pilot executed a total of 10 practice runs. The pilot was already familiar with the simulation and simulation facility before these experiments, and had had two to three hours experience flying this simulation while performing other tasks. During the experiment, the various conditions (combinations of motion system configuration and control system configuration) were presented to the pilot randomly until the necessary number of replications had been obtained.

To answer Question 2, 20 simulation runs were made with the instruments frozen. On 10 of these runs the stability and control augmentation system was on, and on the other 10 runs it was off. The motion system was on for all 20 simulation runs. The control system on and control system off conditions were presented to the pilot randomly. The SCAS on and SCAS off conditions were used in this experiment to see if aircraft handling qualities affected the answer to Question 2.

C. Data Collection Procedure

On each simulation run, data were collected both at the instant of touchdown and during the approach; as both were considered part of a landing. These data were collected in real time by the digital part of the hybrid computer, which stored and created a file of the data during the course of the simulation run, performed the necessary computation, and printed out the data for each run on a line printer after the end of the run.

The data collected at touchdown consisted of the instantaneous values of x, $\dot{x}$, $\dot{z}$, θ, q, y, $\dot{y}$, ϕ, ψ, p, and r. x, y, and z form a right-handed coordinate system with x pointing along the runway away from the runway threshold, and z pointing down. The origin is at the glide path intercept point (GPIP). ϕ, θ, and ψ are the aircraft body axis Euler angles.

Data were collected during the approach to provide a measure of the pilot's tracking performance and to indicate the departure from a nominally three degree glide slope. The data that were collected were the mean and standard deviation of all points on the approach lying between 500 feet altitude and 50 feet altitude. The means and standard deviations collected were of θ, q, Λ, α, ϕ, p, ψ, r, y, and β.

D. Pilot's Background and Experimental Procedures

The single subject pilot for these experiments was an Air Force pilot assigned to the simulation facility. His flying background is summarized as follows:

Age:	29
First Pilot Time:	720 hours
Instructor Pilot Time:	643 hours
Total Pilot Time:	1700 hours
Aircraft Experience:	T-37, T-41, T-39, T-38, O-2A
Type Aircraft Current In:	T-39
Trainer Experience:	T-38, T-37, T-40

The trainer experience of the pilot was in instrument procedures trainers which did not have visual (T-37, T-38, T-40) or motion systems (T-38, T-37). The pilot was briefed on the purpose of the experiments before they were conducted. Since he was assigned to the simulation facility he was already familiar with the conduct of a simulation. He conducted the simulated approaches and landings alone, without the assistance of a copilot, and had no tasks (such as using radios) to perform in addition to landing the aircraft. During the simulation runs, he made comments on what was occurring as appropriate. He was informally debriefed after each run by an observer seated at the copilot position. The observer also noted the pilot's behavior, especially with regard to his division of attention between the visual display and the instruments. The pilot did not know in advance what the particular experiment condition was to be. He always used the direct lift control,

but did not know in advance whether the SCAS could be on or off. When the runs were made with the instruments frozen, he did know in advance that he would not have instruments.

SECTION IV

RESULTS OF THE EXPERIMENTS

This section will present the results of the experiments and a statistical analysis of the results. It first considers each objective individually, and then summarizes the results for the various objectives.

A. Objective 1: Does the motion system affect landing performance?

The data used to satisfy this objective were collected on 40 simulator runs; 10 runs each for the combinations (SCAS, motion), (SCAS, no motion), (no SCAS, motion), and (no SCAS, no motion). The runs were organized as a fractorial experiment with random order of presentation (11). Data were collected during the approach and at the touchdown point.

The classification scheme used for the data denotes the (SCAS, motion) combination as A, (SCAS, no motion) as B, (no SCAS, motion) as C, and (no SCAS, no motion) as D. Table 2 presents the mean and standard deviation of the lateral touchdown parameters for combinations A, B, C, and D.

1. Touchdown Data

It was planned to use an analysis of variance (11) to test for the statistical significance of any motion effects upon touchdown performance. Before this was done, the assumption of the analysis of variance that the variances were homogenous from configuration to configuration was tested using the M test for homogenous, variances (11). For a test at the .05 level for Type I error, the hypothesis of homogenous variances was accepted for the variables x, y, $\dot{x}$, $\dot{y}$, $\dot{z}$, p, and r. The homogenous variance hypothesis was rejected at the .05 level for θ, ϕ, ψ, and q. The data which passed the equal variance test was then analyzed using an analysis of variance procedure for a two-way classification with replication (11). The two factors in the analysis were whether the SCAS was on or off, and whether the motion was on or off. Statistical tests at the .05 level were made of the significance of the main factor effects and the interaction effect.

TABLE 2

LONGITUDINAL TOUCHDOWN PARAMETERS, MOTION/NO MOTION CASES

OBJECTIVE 1

VARIABLE	CONFIGURATION (SCAS, MOTION) A	(SCAS, NO MOTION) B	(NO SCAS, MOTION) C	(NO SCAS, NO MOTION) D		UNITS
x	83.02	191.87	450.86	902.13	Mean	
	556.5	457.42	679.92	999.02	Std. Dev.	Feet
$\dot{x}$	185.44	187.07	182.61	179.79	Mean	
	3.37	6.33	5.27	6.36	Std. Dev.	Ft/Sec
$\dot{z}$	-4.64	-4.30	-5.47	-5.96	Mean	
	2.15	1.90	2.51	2.48	Std. Dev.	Ft/Sec
θ	4.27	4.72	5.88	5.30	Mean	
	.67	2.39	2.50	2.40	Std. Dev.	Deg
q	.45	.50	1.56	.79	Mean	
	.76	.58	.84	2.07	Std. Dev.	Deg/Sec

The analysis of variance for x indicated that control system, motion system, and their interaction were all significant. The mean values for x are plotted in Figure 1. t tests were made of the differences in means between the A (motion, SCAS) and B (no motion, SCAS) cases, and between the C (motion, no SCAS) and D (no motion, no SCAS) cases. When the SCAS was on, the difference in x means for motion on or motion off was not significant at the .05 level. When the SCAS was off, the x mean difference between motion and no motion was significant at the .05 level. This indicates that motion may have affected the longitudinal touchdown point for the configuration with the poorer handling qualities, but did not significantly affect the touchdown point for the configuration with the better handling qualities. The difference in mean touchdown points with the SCAS on versus with the SCAS off would be expected as the aircraft dynamic response would change between the two cases. The sink rate performance is not significantly affected by either control system or motion system. Pilot comments indicated that the pilot was trading off runway longitudinal position for sink rate during this experiment, which would compensate for changing aircraft dynamics.

The y analysis of variance resulted in control system, motion system, and the interaction being nonsignificant. For $\dot{x}$, the motion system and interaction were not significant, but the control system was as would be expected for changing aircraft dynamics. The means of Table 2 show that the pilot landed slightly slower in the bare airframe cases (Cases C and D).

The y, z, and r analyses of variance supported the hypothesis that neither control system, motion system, or the interaction was significant. The p analysis of variance showed that neither the control system nor the motion system were significant factors, but the F ratio for the interaction was significant, being slightly larger than the test value. The means for p given in Table 3 are plotted in Figure 2. The figure shows a crossed interaction, with A (SCAS, motion) and D (no SCAS, no motion) having negative mean roll rates at touchdown, and B (SCAS, no motion) and C (no SCAS, motion) having positive mean roll rates at touchdown. This might have resulted from biases in the simulation. No change in the pilot's task could be found which would explain this type of interaction.

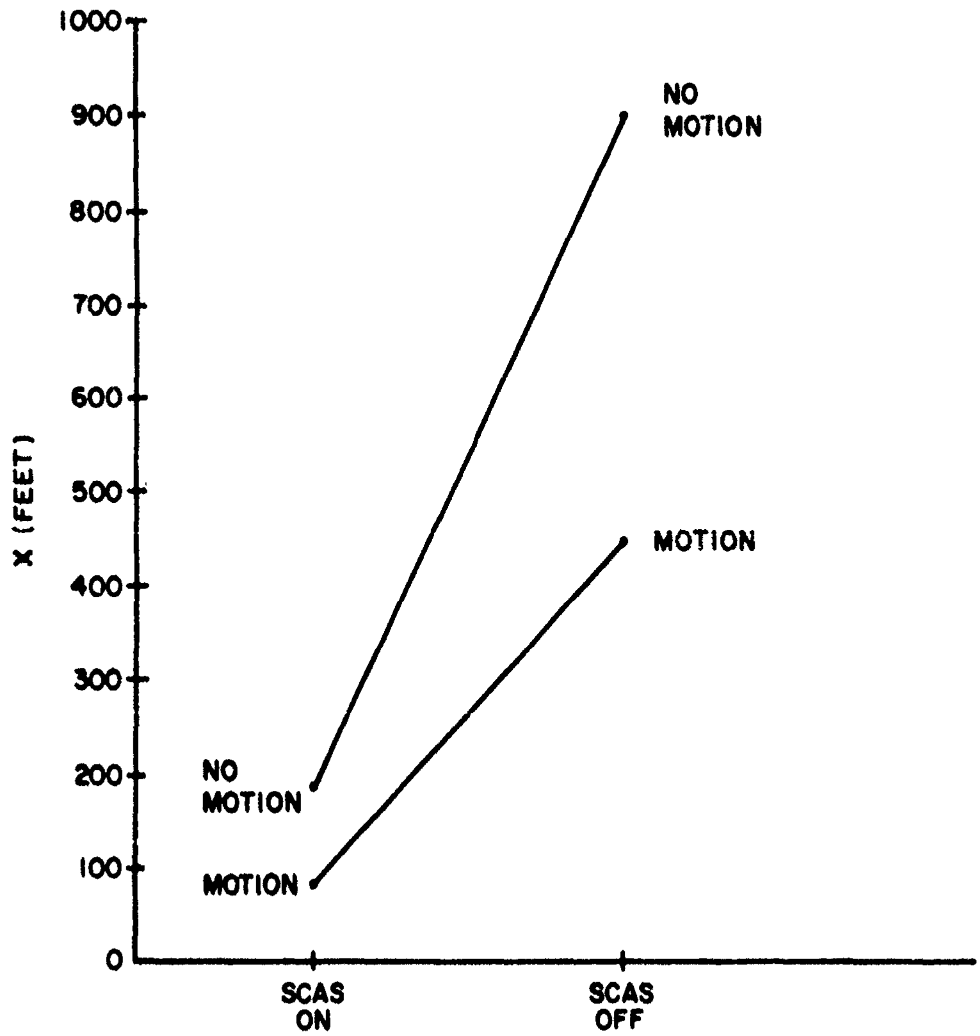

Figure 1. Mean Longitudinal Touchdown Points for (SCAS, Motion), (SCAS, No Motion), (No SCAS, Motion), and (No SCAS, No Motion) Cases

TABLE 3

LATERAL TOUCHDOWN PARAMETERS, MOTION/NO MOTION CASES

CBJECTIVE 1

VARIABLE	CONFIGURATION					
	(SCAS, MOTION) A	(SCAS, NO MOTION) B	(NO SCAS, MOTION) C	(NO SCAS, NO MOTION) D		UNITS
y	15.11	14.77	-4.31	1.94	Mean	
	16.22	21.07	13.50	25.08	Std. Dev.	Feet
$\dot{y}$	-.63	.20	.85	1.07	Mean	
	2.86	4.75	3.53	2.99	Std. Dev.	Ft/Sec
ϕ	.45	.80	.47	1.04	Mean	
	1.18	1.62	3.73	6.05	Std. Dev.	Deg
ψ	89.49	89.36	88.94	88.19	Mean	
	.60	1.16	1.59	2.39	Std. Dev.	Deg
p	-.43	1.29	.78	-.95	Mean	
	2.15	1.88	2.13	3.25	Std. Dev.	Deg/Sec
r	-.57	-.27	.29	-.05	Mean	
	1.08	1.00	1.43	1.72	Std. Dev.	Deg/Sec

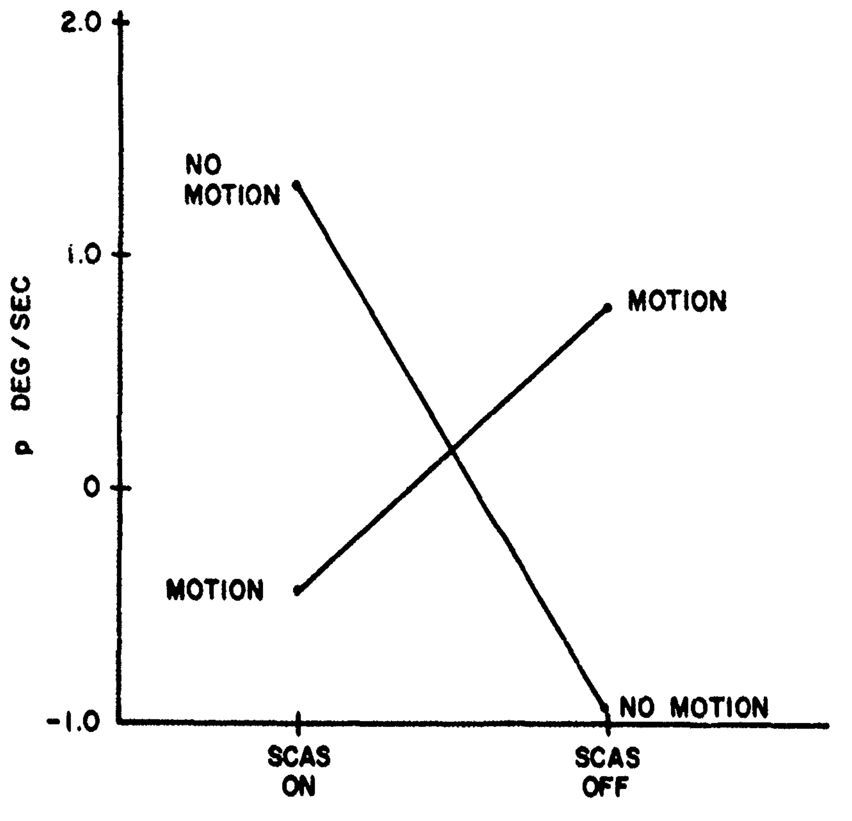

Figure 2. Mean Values of p at Touchdown for (SCAS, Motion), (SCAS, No Motion), (No SCAS, Motion), and (No SCAS, No Motion) Cases

The variables which failed the homogenous variance test were θ, ϕ, ψ, and q. θ failed the test because the standard deviation for Case A was considerably smaller than the other standard deviations; while q failed the test because the standard deviation for Case D was considerably larger. For ϕ and ψ, whether the control system was on appears to strongly affect the standard deviations, and they show a trend of increasing from Case A to Case D.

Since the variables θ, ϕ, ψ, and q failed the homogenous variance test, an analysis of variance could not be applied to this data without violating the assumptions of the analysis. However, it was still desired to analyze this data statistically to test for the presence of motion effects.

Therefore, to determine if the motion system being on or off had a significant effect upon the standard deviations of θ, ϕ, ψ, and q, F tests (11) were made at the .05 significance level of the hypotheses that the standard deviation of Case A was equal to the standard deviation of Case B for θ, ϕ, ψ, and q, and similarly for the Case C standard deviations equaling the Case D standard deviations. In all cases, the hypotheses were accepted that chance could result in the differences in the standard deviations, and that there was no difference due to the motion being on or off.

To check out the simulation, tests were made to see if certain means did not differ significantly from zero. It would be expected a priori that x and q of the longitudinal variables, and y, $\dot{y}$, ϕ, ψ, p, and r of the lateral variables could have zero or near zero means, and that the means of the other variables would not be zero.

t tests (11) were made of the hypotheses that the means of the variables for the Cases A, B, C, and D were zero. The .05 significance level was used, and the test for ψ was actually for a non zero difference from 90 degrees, as that was the runway heading in the simulation. The results of these tests are given in Table 4. The non-zero means for y and ψ could have resulted from biases in the simulation, and are on

TABLE 4

CHECK ON REASONABLENESS OF SIMULATION:
RESULTS OF t TESTS FOR ZERO MEANS, TOUCHDOWN PARAMETERS

LONGITUDINAL VARIABLES	ZERO MEAN HYPOTHESIS ACCEPTED (SCAS, MOTION) A	(SCAS, NO MOTION) B	(NO SCAS, MOTION) C	(NO SCAS, NO MOTION) D
x	Yes	Yes	Yes	No
$\dot{x}$	No	No	No	No
$\dot{z}$	No	No	No	No
θ	No	No	No	No
q	Yes	No	No	Yes
LATERAL VARIABLES				
y	No	Yes	Yes	Yes
$\dot{y}$	Yes	Yes	Yes	Yes
ϕ	Yes	Yes	Yes	Yes
ψ	No	Yes	Yes	No
p	Yes	Yes	Yes	Yes
r	Yes	Yes	Yes	Yes

the order of 15 feet and half of a degree. These magnitudes are not important practically. The q means which were significantly different from zero were of the order of .5 deg/sec and 1.5 deg/sec, which are practically small values.

Surveying all of the touchdown data, it is consistent with an aircraft making a normal landing at a high sink rate. Since the mean of q is at zero or has a small value, the aircraft has essentially completed the attitude change associated with flare. $\dot{x}$, $\dot{z}$, and θ have values consistent with a flared aircraft, and all of the other variables are essentially zero mean. The motion system being on or off possibly affects only the along track touchdown point for the no SCAS condition, causing it to have a tendency to be long. Whether the control system is on or off (i.e., aircraft dynamics) has a definite effect upon the touchdown performance, as turning off the control system tends to result in a longer along track touchdown point, slightly slower speed, slightly higher pitch angle, and greater variation in q, ϕ, and ψ. These effects due to the control system, especially the greater variation in ϕ, and ψ, were due to the less favorable handling qualities of the bare airframe, especially in the lateral axis. The pilot commented on the difference in aircraft handling qualities, and the additional work entailed when the SCAS was turned off.

2. Approach Data

The data collected during the approach were the mean and standard deviation of θ, q, Δ, α, ϕ, p, ψ, r, y, and β for each simulation run. The raw data used to compute the means and standard deviations consisted of samples collected once every .1 second while the simulated aircraft was between the altitudes of 500 feet and 50 feet. The means and standard deviations were computed on line, and the only data printed out for analysis were the means, the standard deviations, and the number of points used to compute the means and standard deviations. These means and standard deviations were then used to compute overall means for the Cases A, B, C, and D, and to compute pooled estimates of the standard deviations (11) for the Cases A, B, C, and D. Tables 5 and 6

present the overall means and the pooled estimate standard deviations for θ, q, Δ, α, ϕ, p, ψ, r, y, and β for Cases A, B, C, and D.

To provide an indication if a motion on/motion off effect was present in the approach data, a series of F tests were made of the hypothesis that differences in standard deviation between Case A and Case B, and between Case C and Case D, were due solely to chance. If no motion effects were present, the hypothesis that the standard deviations were equal should be accepted. The tests were made at the .05 significance level for the variables θ, q, Δ, α, ϕ, p, ψ, r, y, and β. The hypothesis of equal variances was rejected only for the Case A versus Case B comparison of ϕ, and was accepted for all of the other 20 comparisons. As in only one out of 20 comparisons was the equal variance hypothesis rejected, and in this case the difference was only on the order of 0.5 degree; it is concluded that the approach standard deviations contain negligible effects due to the motion drives being on or off.

Comparisons of the means for Case A versus the means for Case B, and of the means for Case C versus the means for Case D were also made using the t test with a .05 significance level. The hypothesis being tested was that the means were equal, which would be expected if no effects due to motion were present. The results of the tests are presented in Table 7.

For the two Cases (A and B) where the control system was on and motion was varied, no difference in means between motion on or motion off was detected for the angular rates q, p, and r, and for the bank angle ϕ. Differences in the means as motion varied were detected in θ, Δ, and α in the longitudinal axis, and in ψ, y, and β in the lateral axis. In Case B, when the motion was off, the Λ mean indicates that the pilot did not "duck under" a nominal three degree glide slope to the extent that he did in Case A, and that he had a slightly larger average pitch and angle of attack. "Duck under" is defined in this context as the aircraft's average flight path lying below the three degree glide slope, and is a normal phenomena in visual landings. Although the θ and α differences are statistically significant, they amount to only a few tenths of a degree, which is not a practical difference.

TABLE 5

LONGITUDINAL APPROACH STATISTICS, MOTION/NO MOTION CASES

OBJECTIVE 1

VARIABLE	CONFIGURATION (SCAS, MOTION) A	(SCAS, NO MOTION) B	(NO SCAS, MOTION) C	(NO SCAS, NO MOTION) D		UNITS
θ	1.622	1.948	1.555	2.102	Mean	
	.478	.502	.933	1.077	Std. Dev.	Deg
q	-.0035	-.004	-.002	.007	Mean	
	.309	.348	.866	.888	Std. Dev.	Deg/Sec
Δ	-24.6	-14.6	-27.6	-13.7	Mean	
	9.36	11.38	11.77	13.67	Std. Dev.	Feet
α	4.716	4.880	4.442	5.131	Mean	
	.628	.653	.936	.964	Std. Dev.	Deg

TABLE 6

LATERAL APPROACH STATISTICS, MOTION/NO MOTION CASES

OBJECTIVE 1

VARIABLE	CONFIGURATION (SCAS, MOTION) A	(SCAS, NO MOTION) B	(NO SCAS, MOTION) C	(NO SCAS, NO MOTION) D		UNITS
ϕ	.449	.597	1.074	1.096	Mean	
	1.185	1.747	3.387	3.281	Std. Dev.	Deg
p	-.031	.035	.032	.018	Mean	
	1.598	1.814	2.375	2.478	Std. Dev.	Deg/Sec
ψ	89.525	88.921	88.434	88.392	Mean	
	.992	1.098	1.315	1.527	Std. Dev.	Deg
r	.044	.022	.069	.013	Mean	
	.827	.862	1.193	1.243	Std. Dev.	Deg/Sec
y	-4.4	22.8	-4.5	-3.3	Mean	
	27.0	31.9	25.4	19.6	Std. Dev.	Feet
β	.394	.921	1.476	1.598	Mean	
	1.033	1.285	1.846	1.933	Std. Dev.	Deg

TABLE 7

TESTS FOR MOTION ON/MOTION OFF EFFECTS:
RESULTS OF t TESTS FOR EQUAL MEANS, APPROACH DATA

LONGITUDINAL VARIABLES	ACCEPT THE HYPOTHESIS	
	SCAS ON MOTION = NO MOTION	SCAS OFF MOTION = NO MOTION
	A = B	C = D
θ	NO	NO
q	YES	YES
h	NO	NO
α	NO	NO
LATERAL VARIABLES		
ϕ	YES	YES
p	YES	YES
ψ	NO	YES
r	YES	YES
y	NO	YES
β	NO	YES

For the two Cases (C and D) where the control system was off, the only differences in means detected were for θ, Δ, and α in the longitudinal axis. Once again, the no motion case was associated with a lesser "duck under" of a nominal three-degree glide slope and slightly greater average pitch and angle of attack. The θ and α differences amounted to about a half degree which is not a practical difference. For the control system off cases, there were no differences in means in the lateral axis.

Considering all of the comparisons of means to determine if a motion effect possibly exists, it seems that any motion effect on the pilot's performance during approach and landing is slight. The p, q, and r means exhibited no motion differences, and would be most closely related to the pilot's control actions. The main effect that the motion being on or off is related to is the average amount by which the pilot "ducks under" a nominal three-degree glide slope, and associated changes in the average pitch and angle of attack.

t tests were also performed to determine which means of the approach data did not differ significantly from zero. These tests were to check on the reasonableness of the simulation. The .05 level was used for the test of significance. For all four cases, the q, p, and r means were determined to not differ significantly from zero, while all of the other means did differ significantly from zero. The ϕ, ψ, y, and β means differing from zero agree with the pilot comments that it seemed to him that a slight crosswind existed in the simulation. This slight crosswind could have resulted from non-zero means in the gust model, but no gust statistics were available to check for this.

Summarizing the data analysis from the point of view of whether an effect was present due to the motion system being on or off at touchdown the only significant effect found due to the motion system was a tendency to land slightly longer when the motion was off. This tendency to land long agrees with the possible motion effect found in the approach data, namely a tendency for the pilot to "duck under" a nominal three-degree

glide slope less when the motion was off. Both the tendency to land long and to "duck under" less could be due to the pilot having more confidence when the motion was on. Throughout the data, the effect of the control system being on or off upon the landing performance was much greater than any motion effect.

It should be noted that it was usually possible for the pilot to state during the course of the simulation whether the motion system was on or off. This was due to the vibration level in the simulator being higher when the motion was on, even if the simulated aircraft was not making noticeable motions

B. Objective 2: Can the simulator be landed without the use of the cockpit instruments?

The data used to satisfy this objective were collected on 21 simulator runs; 10 runs with the control system on and the cockpit instruments frozen at their initial trim values, and 11 runs with the control system off and the cockpit instruments frozen at the initial trim values. The control system on configuration was denoted Case E, and the control system off configuration was denoted Case F. The 21 runs for Case E and F were arranged so that the pilot was presented Case E or Case F at random. For all of these runs, the motion system was on.

For this experiment, a successful landing was defined to occur if the aircraft landed on the runway, it remained on the runway during rollout, and it did not touch down with excessive rates (structural limits of aircraft). If these criteria were not met, the landing was considered to be a crash.

In a qualitative sense, this objective was satisfied just by being able to complete the 21 runs without any of them being crashes. Instead, the landings were successful and qualitatively similar to the simulated landings made with the instruments operating. Touchdown and approach data on the no instrument simulation runs were collected in a manner identical to that used for objective 1, and will be presented now.

1. Touchdown Data

The means and standard deviations of the touchdown parameters are presented in Table 8 for the longitudinal variables of Cases E and F, and in Table 9 for the lateral variables of Cases E and F.

The effect of the instruments being frozen or not was investigated by comparing Case A (SCAS, motion, instruments) with Case E (SCAS, motion, no instruments), and by comparing Case C (no SCAS, motion, instruments) with Case F (no SCAS, motion, no instruments). These cases differed only in whether the instruments were frozen or not. Cases A and E both had the SCAS on, but Case E had the instruments frozen forcing the pilot to rely upon the visual display to land the aircraft. Cases C and F both had the control system off, with the pilot forced to use the visual system in Case F. Comparisons were made of both the touchdown data and the approach data. The touchdown data were compared by conducting F tests of the hypotheses that the standard deviations differed only due to chance, and then using t tests to test for equal means for those variables for thich the equal standard deviation hypothesis was accepted. The approach data were compared by performing F tests of the hypotheses that the standard deviations were equal, and doing t tests to detect non-zero means.

Performing the F tests at the .05 significance level, the Case A (SCAS, instruments) versus Case E (SCAS, no instruments) touchdown data standard deviation comparison showed that significant differences existed only for $\dot{x}$, θ, and $\dot{y}$. The Case C (no SCAS, instruments) versus Case F (no SCAS, no instruments) standard deviation comparison yielded a significant difference only for q. Comparing the $\dot{x}$, θ, and $\dot{y}$ standard deviations for Cases A and E with the standard deviations for all of the cases, the $\dot{x}$ standard deviation for Case E is considerably larger than the standard deviation for any other case; the θ standard deviation is considerably smaller for Case A than for any other case; and the $\dot{y}$ standard deviation for Case E is smaller to the values for Cases A, B, and E, while the Case F standard deviation for q is next to the largest. Except for the $\dot{x}$ and θ standard deviations of Case E and the larger q

TABLE 8

LONGITUDINAL TOUCHDOWN PARAMETERS, NO INSTRUMENTS CASES

OBJECTIVE 2

VARIABLE	CONFIGURATION (SCAS, MOTION) E	(NO SCAS, MOTION) F		UNITS
x	27.5	679.2	Mean	
	919.21	869.44	Std. Dev.	Feet
$\dot{x}$	169.93	166.93	Mean	
	19.91	8.19	Std. Dev.	Ft/Sec
$\dot{z}$	-5.86	-5.29	Mean	
	3.99	1.59	Std. Dev.	Ft/Sec
θ	8.07	9.10	Mean	
	3.89	1.98	Std. Dev.	Deg
q	.34	1.58	Mean	
	.82	1.36	Std. Dev.	Deg/Sec

TABLE 9

LATERAL TOUCHDOWN PARAMETERS, NO INSTRUMENTS CASES

OBJECTIVE 2

VARIABLE	CONFIGURATION (SCAS, MOTION) E	(NO SCAS, NO MOTION) F		UNITS
y	15.87	1.87	Mean	
	26.59	27.52	Std. Dev.	Feet
$\dot{y}$	-.10	-1.19	Mean	
	1.27	3.58	Std. Dev.	Ft/Sec
ϕ	-.29	.68	Mean	
	.77	3.12	Std. Dev.	Deg
ψ	90.19	90.06	Mean	
	.95	1.62	Std. Dev.	Deg
p	-.01	-.30	Mean	
	1.14	2.19	Std. Dev.	Deg/Sec
r	.30	-.38	Mean	
	1.47	.93	Std. Dev.	Deg/Sec

standard deviation of Case F, the absence of instruments did not appreciably change the standard deviations of the touchdown variables. The $\dot{y}$ standard deviation with SCAS on is actually larger with instruments than without, and is small in both cases. The larger $\dot{x}$ standard deviation is probably caused by the difficulty of flying an aircraft when no air speed indication is available. The larger θ and q standard deviations may be due to difficulty in judging when to start to flare caused by the larger speed variations.

t tests for equal means at the .05 significance level were made for x, z, q, y, ϕ, ψ, p, and r in the Case A versus Case E comparison, and x, $\dot{x}$, $\dot{z}$, θ, y, $\dot{y}$, ϕ, ψ, p, and r in the Case C versus Case F comparison. No significant differences in means were detected by these tests, so the hypotheses that all of these means were equal was accepted. t tests were also made of the hypotheses that the $\dot{y}$ means of Case A and Case E were zero, and these hypotheses were accepted at the .05 significance level. A t test of the hypothesis that the θ means were equal between Cases A and E rejected the hypothesis. Similar t tests on the mean q for Cases C and F being zero resulted in the hypotheses that the mean q was zero being rejected for Case C and accepted for Case F. Considering the results of all the tests, the mean values of the touchdown parameters with and without instruments are identical execpt for differences in forward velocity and pitch, and a non-zero mean pitch rate when instruments are available and the control system is off. The non-zero mean pitch rate is probably caused by a delayed flare. The differences in forward velocity and pitch are probably caused by the pilot's lack of airspeed information.

2. Approach Data

The standard deviations of the approach data were compared using F tests at the .05 significance level to test the hypotheses that the standard deviations were equal. For the Case A versus Case E tests, the hypothesis of equal standard deviations was accepted only for ψ. Of the remaining nine comparisons, the Case E standard deviation was larger four times (θ, q, α, β), and the Case A standard deviation was larger five times (Λ, p, ϕ, r, y). The largest relative difference was in θ, and mounted to .68 degree, which is not an important difference.

For the Case C versus Case F tests, the hypothesis of equal standard deviations was accepted for θ, Λ, α, p, ψ, r, and β. It was not accepted for q, ϕ, and y. In the q, ϕ, and y cases, the Case F (no instruments) standard deviation was larger for ϕ and y, and smaller for q. The difference in q standard deviation is on the order of .1 deg/sec, which is not of practical importance. The ϕ difference is on the order of a degree, while the y difference is on the order of 10 feet. These increases indicate a slight degradation of performance in the lateral axis for flying the SCAS off aircraft when no instrument information was available.

During the approach, since the pilot did not know his airspeed, he left his throttle at its initial setting until he retarded it during flare. This may account for the larger ϕ, α, and β standard deviations of Case E (SCAS, no instruments) compared to Case A (SCAS, instruments), as the aircraft modes were not excited as much for the better handling aircraft thus allowing the effect of airspeed not being controlled to be seen more clearly.

t tests at the .05 significance level of the means of the approach data showed that the mean values of p, q, and r for Cases A, C, E, and F did not differ significantly from zero, except for q of Case E, while the means of the other approach variables did differ from zero. The mean q of Case E was .039 deg/sec, which is not of practical magnitude. Comparing the means for Cases E and F against the means for Cases A and C (from Tables 5, 6, 10, and 11), it is seen that the instruments being frozen resulted in a greater mean pitch angle, larger "duck under", higher angle of attack, somewhat smaller roll, heading, and sideslip means, and mean lateral deviations of opposite sign. The most pronounced differences are the greater "duck under" when only visual information is present, in conjunction with a larger mean pitch angle and angle of attack, and the sideslip and lateral deviation changes. The sideslip and lateral deviation differences are probably due to a changing bias in the gust model.

TABLE 10

LONGITUDINAL APPROACH STATISTICS, NO INSTRUMENTS CASES

OBJECTIVE 2

VARIABLE	CONFIGURATION (SCAS, MOTION) E	(NO SCAS, MOTION) F		UNITS
θ	3.408	2.652	Mean	
	1.156	1.011	Std. Dev.	Deg
q	.039	.013	Mean	
	.375	.727	Std. Dev.	Deg/Sec
Δ	-34.07	-29.67	Mean	
	14.75	12.95	Std. Dev.	Feet
α	6.581	5.652	Mean	
	.989	.819	Std. Dev.	Deg

TABLE 11

LATERAL APPROACH STATISTICS, NO INSTRUMENTS CASES

OBJECTIVE 2

VARIABLE	CONFIGURATION (SCAS, MOTION) E	(NO SCAS, NO MOTION) F		UNITS
ϕ	.097	.513	Mean	
	.830	4.555	Std. Dev.	Deg
p	-.035	-.033	Mean	
	.887	2.472	Std. Dev.	Deg/Sec
ψ	90.095	89.315	Mean	
	.900	1.381	Std. Dev.	Deg
r	.018	-.005	Mean	
	.507	1.042	Std. Dev.	Deg/Sec
y	17.91	17.37	Mean	
	21.26	38.06	Std. Dev.	Feet
β	-.147	.392	Mean	
	.686	2.069	Std. Dev.	Deg

3. Summary of the Effect of Withholding Instrument Information

This section will recapitulate the results of subsections 1 and 2.

When the pilot was forced to use only visual information to fly the simulation, he could not directly control his airspeed and made his landings at a lower velocity. He tended to "duck under" a nominal three-degree glide slope to a greater extent than when the instruments were available, and during the approach he kept the aircraft pitched up slightly more, with a slightly higher angle of attack. His approach tracking performance, as measured by the standard deviations of the approach data, was relatively unaffected by the lack of instrument data. Some slight degradation might be attributed to the SCAS being off. Despite these changes in performance, when the cockpit instruments were frozen, the simulator definitely could be landed successfully according to the definition of a successful landing given previously.

4. SCAS On/SCAS Off Effects

To determine if the control system being on or off significantly affected the touchdown parameters when the instruments were frozen, F tests were made of the hypotheses that the standard deviations for Cases E and F for the various variables differed only due to change. These tests were made at the .05 significance level. Of the 11 variables tested, only the standard deviations associated with ϕ were found to differ significantly. This difference is consistent with the pilot comments that the lateral axis was much more difficult to fly when the control system was off than when it was on, due to the poorer handling qualities of the aircraft with the control system off. Dutch roll was especially noticeable with the SCAS off.

t tests were also made of the hypotheses that the means of the variables at touchdown were equal for Cases E and F. The significance level used was .05, and a significant difference was found only for q. This might indicate a difference in the flare maneuver due to the presence or absence of the control system.

Using the results of the tests for equal standard deviations and equal means, overall means and pooled estimates of the standard deviations were formed for the touchdown parameters. t tests were then performed at the .05 significance level, to test the hypotheses that the means were zero. The means of $\dot{x}$, $\dot{z}$, θ, and q were significantly different from zero, while the means of x, y, $\dot{y}$, ϕ, ψ, p, and r did not differ from zero more than could be expected from chance. This indicates that the aircraft probably had not quite completed its flare when it touched down, and it was not biased away from touching down with its wings level. The flare not quite being completed is probably due to its being initiated late.

Table 10 presents the overall means and pooled standard deviations for the longitudinal variables, and Table 11 presents them for the lateral variables. The overall means and pooled estimate standard deviations for the approach data for Cases E and F were computed using exactly the same procedure given for Cases A, B, C, and D in the preceeding section.

F tests were made at the .05 significance level of the hypotheses that the standard deviations for Case F were the same as the standard deviations for Case E. The hypothesis of equal standard deviations was rejected for q in the longitudinal axis, and for ϕ, p, ψ, r, y, and β in the lateral axis. The equal standard deviation hypothesis was accepted only for θ, Λ, and α in the longitudinal axis. The results of these tests are consistent with the pilot comments that the no SCAS case was much more difficult to fly, especially in the lateral axis. The significant differences in standard deviations are all associated with the no control case standard deviations being larger than the with control case standard deviations, indicating that the pilot's tracking performance during the approach was degraded by the absence of the SCAS, a result which is expected.

As a check on the reasonableness of the simulation, t tests were also made to test the hypotheses that the overall means were zero. The results of tests at a significance level of .05 are given in Table 12.

TABLE 12

CHECK ON REASONABLENESS OF SIMULATION: RESULTS OF t TESTS FOR NON-ZERO MEANS OF CASE E AND CASE F APPROACH STATISTICS

VARIABLE	CASE	
	(SCAS, MOTION) E	(NO SCAS, MOTION) F
LONGITUDINAL VARIABLES	.05	.05
θ	YES	YES
q	YES	NO
Δ	YES	YES
α	YES	YES
LATERAL VARIABLES		
ϕ	YES	YES
p	NO	NO
ψ	YES	YES
r	NO	NO
y	YES	YES
β	YES	YES

Yes = Non-zero mean hypothesis accepted.

No = Zero mean hypothesis accepted.

The tests indicate that the means of the angular rates p q, and r were zero, except for q of Case E. The non-zero q mean for Case E is practically negligible being only .039 deg/sec. The non-zero menas of h, θ, and α indicate that the pilot pitched the nose of the aircraft up above the trim condition, and "ducked uner" a nominal three-degree glide slope. The non-zero means of y, β, ψ, and ϕ indicate that the simulated aircraft sideslipped slightly during the approach and was offset slightly from the extension of the runway centerline. The offset was the same for both with and without the control system, but the average sideslip changed direction, as did the mean deviation of the heading from the runway heading of 90 degrees. The means in the lateral variables are small and are not likely to be related to the SCAS being off or on, and might not be repeatable in a future simulation.

C. Objective 3: Can the simulator be landed with conventional aircraft values of sink at touchdown?

The data available to answer this objective consisted of the the value of the sink rate at touchdown on 128 simulated landings by the same pilot. These 128 sink rate values were listed chronologically, and examined for traces of learning behavior and the effects of changing the experiment being performed. They were also classified as to the various landing strategies used by the pilot.

The data most readily available concerning landing sink rates of actual aircraft is in the form of a mean sink rate or nominal sink rate, and sometimes a standard deviation. Typical values given are +2 ft/sec mean with a standard deviation of .5 ft/sec.

To provide comparable data from the simulation runs, the mean and standard deviation of the touchdown sink rate were computed for groups of 10 runs, with the division into groups being done on a chronological basis. The only exceptions to this method of forming groups were the last two groups, which were of seven and 11 runs respectively, and divided that way because of a change in pilot strategy and the fact that 128 is not evenly divisible by 10. The means and standard deviations are

given for each group, arranged in chronological order, in Table 13. Figure 3 shows a graph of all the sink rate data, with the group means and plus or minus one standard deviation superimposed on the graph.

As noted on Table 13, several different experiments were conducted during the period in which the sink rates were collected. The first experiment, conducted between runs one and 63, was the experiment which was reported on above under Objective 1. The second experiment, conducted between runs 64 and 87, was the experiment on the effect of freezing the instruments and forcing the pilot to use only the visual display, which was reported on above under Objective 2. Runs 88 through 128 were collected during an experiment to investigate various modifications of the motion drive system, which is reported on in Reference 12.

Additional information required to interpret Table 13 is that between runs 72 and 73 occurred a three-week break, and that starting with run 118 the pilot changed his landing strategy.

Examining the data of Table 13, it appears that a learning effect is present throughout the first 40 runs, and this learning is characterized by an initial improvement during the first 10 runs, then a plateau in performance, and about run 40 a sudden step improvement in performance. The pilot's sink rate performance then appears to stabilize until after the three-week break, when either the break resulted in the pilot having to relearn to his previous level of proficiency and/or the varying experiment conditions (no instruments or varying motion cues) disturbed his performance. The sink rate performance then approaches the previous level until run 118, at which point the pilot changed his landing strategy, and his sink rate performance shows a sudden step improvement. The final sink rate performance is comparable to that found in actual aircraft operations.

The most interesting part of the data is the sudden decrease in sink rate following run 117, as it was associated with the pilot saying he changed his landing strategy. The first strategy used by the pilot basically involved trying to trade off longitudinal touchdown position

TABLE 13

TOUCHDOWN SINK RATE MEANS AND STANDARD DEVIATIONS
(SCAS ON/OFF, MOTION ON/OFF, INSTRUMENT ON/OFF CONDITIONS MIXED)

GROUP	RUNS	MEAN $\dot{z}$	$\dot{z}$ STANDARD DEVIATION (FT/SEC)	COMMENTS
1	1 to 10	+7.81	3.18	
2	11 to 20	+6.63	2.16	
3	21 to 30	+6.34	2.37	Motion on/motion off experiment, four
4	31 to 40	+6.00	2.31	different conditions.
5	41 to 50	+4.04	1.37	
6	51 to 60	+4.09	1.97	
7	61 to 70	+4.38	1.59	
				Three-week break
8	71 to 80	+4.76	1.75	No instruments experiment, two different conditions.
9	81 to 90	+6.58	3.67	
10	91 to 100	+6.37	2.39	
11	101 to 110	+4.71	2.39	Varying motion drive experiment. Landing
12	111 to 117	+4.51	1.15	strategy change.
13	118 to 128	+1.94	.57	

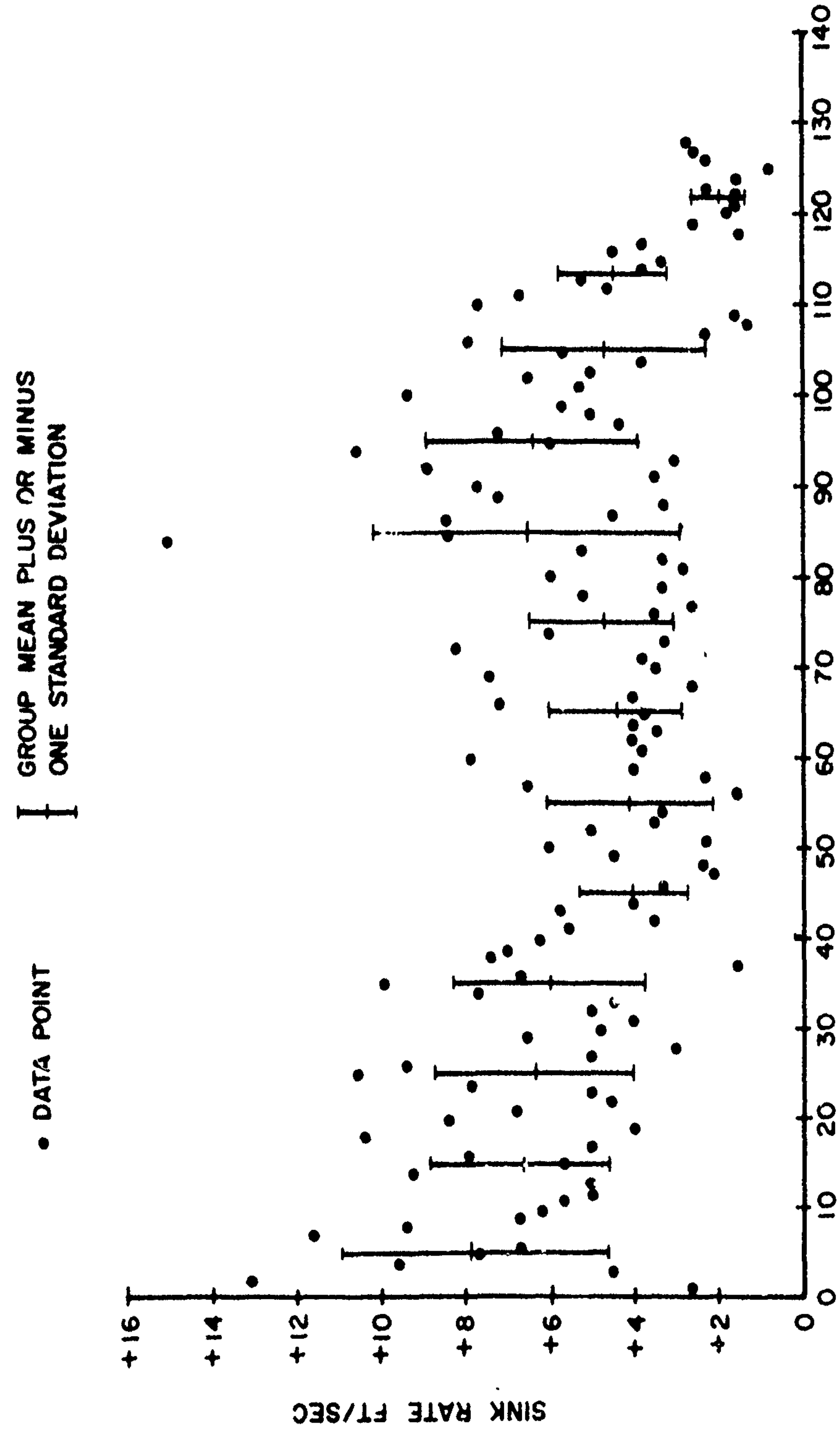

Figure 3. Graph of Chronological Record of Touchdown Sink Rates

for sink rate. If the pilot detected that he was going to land hard, he would pull back and try to float the aircraft down the runway until the sink rate had decreased, and then touchdown. During the flare, the pilot would retard the throttles as would be normal in an aircraft.

The change that resulted in the second strategy was when the throttles were retarded. In the second strategy, the pilot did not retard the throttles during flare, but waited until after touchdown and then chopped the throttles. This change in the time when the throttles were cut improving the realism of the touchdown sink rates indicates the possibility that the engine thrust response of the simulator is more rapid than that of the actual engines, or the possibility that the pilot cannot accurately judge heights at simulated low altitudes and consistently underestimates his height close to touchdown in the simulation. Other than the change in the timing of the throttle chop, the second strategy was identical with the first strategy.

The pilot suggested the change in landing strategy on his own initiative, as he felt that retarding the throttles after touchdown was more appropriate for this aircraft. The definition of the landing task given to the pilot was not changed, nor were the roll out rules.

It should be noted that in an actual aircraft, delaying retarding the throttles until after touchdown also results in decreasing the touchdown sink rate. Therefore, the possibility exists that the reduction in sink rates in the simulator due to delaying the throttle retardation parallels the reduction in sink rate which a delayed throttle retardation would produce in a real aircraft. In this case, the simulator sink rates would still be about twice the sink rates of an actual aircraft flown with the same strategy.

For runs one through 63, qualitative data on the pilot's inside cockpit/outside cockpit scan pattern were available. These data were collected by an observer in the copilot seat noting and recording the pilot's eye motions. The observations indicated that when instruments

were available, the pilot divided his time approximately equally between the instruments and the out of the cockpit visual scene. Most scans either inside or outside were of relatively long duration (several seconds at least), but occasionally there would be bursts of short, rapid scans back and forth from the visual display to the instruments and vice versa. The bursts of numerous quick scans to the instruments occurred more frequently when the control system was off, and their occurrence initially could be used to predict whether the control system was off or on. As the pilot became more experienced in flying the simulator, the burst of short scans behavior came to be associated with both control system off and control system on runs, so that it could no longer be used for prediction. Also, as the pilot gained more experience with the simulator, the duration of the scans to the out of cockpit visual scene increased, and the length of the instrument scans decreased. It should be noted that all of the flare and touchdowns were made while referring only to the external visual display.

One final point to be observed from Table 13 is that except for the initial learning period and the improvement in performance following the strategy change, the means and standard deviations for the various groups are quite similar even though the motion cues being provided were changing, the dynamics of the aircraft and control system were changing, and whether instruments were available or not changed. The only system in the simulation which did not change was the visual system.

During a visual approach and landing, the pilot receives most of his information about the aircraft's position and motion from what he can see outside the aircraft. In a simulation, this type of information is provided by the visual system. Thus, it would be expected that sink rates would be relatively insensitive to cue changes which did not involve the visual presentation.

Certain statistical tests were performed to check the reasonableness of the observations made from Table 13. For the first 12 groups, an M test for homogenous variances at the .05 significance level did not reject the hypothesis that the population standard deviation was

constant from group to group. A pooled estimate of the standard deviation was then calculated. The pooled estimate value of 2.31 was then compared with the standard deviation of the thirteenth group (of value .57) using an F test and the hypothesis of equal population standard deviations rejected at the .05 level.

For the first 12 groups, a test for a trend in means (11) was performed, and this test indicated that a trend was present and of a smooth curve rather than oscillatory type. A .95 confidence interval (11) of (-1.56, -2.32) was calculated for the thirteenth group, and it could be noted that the means of the 12 other groups all lie outside of this confidence interval.

The presence of a smooth curve trend agrees with a learning curve interpretation of the changes in mean sink rate. The fact that the confidence interval for the mean of the thirteenth group does not contain any of the means of the other groups indicates that there was a definite change in the sink rates between the thirteenth group and the other groups.

D. Summary of Experimental Results

This section presents a synopsis of the results of the experiments uncluttered by detail. The effects of the SCAS being on or off, the motion system being on or off, and whether the instruments were driven or not are treated.

The only effects observed due to motion cues were a lesser tendency to "duck under" the nominal glide slope when the motion was off combined with a tendency to land further down the runway. The tendency to land further down the runway was in conjunction with a similar but more prominent tendency associated with the control system being off, and was statistically significant only when the SCAS was off.

The lack of an appreciable effect due to the motion system being on or off is not unexpected for the landing task. The standard deviations of p, q, and r are all of the same magnitude or smaller than the

thresholds for human sensing of these angular velocities (13) (14), so motion cues would not be expected to be important in the task simulated.

When the pilot was forced to fly the simulator using only the visual display, he flew more slowly and his airspeed varied more because he could not determine it. He "ducked under" the nominal glide slope to a greater extent, and the control system being off increased the scatter in some of the aircraft lateral variables. Despite these differences, the pilot was able to fly and land the simulator successfully.

The pilot not retarding the throttles until after touchdown allowed him to obtain touchdown sink rates representative of actual aircraft. Except for learning about the throttle retardation, the pilot's learning curve for landing the simulator seemed to have flattened out by the time he had completed 40 simulator runs.

The largest effects observed during the experiments were due to the control system. The aircraft was more difficult to fly when the SCAS was off, and this was reflected in more scatter in the aircraft variables during the approach and at touchdown.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

Organized by objective, the conclusions of these experiments are as follows:

1. The limited motion system used in these experiments had minor effects upon the single subject pilot's landing performance based upon the touchdown and approach statistics presented in the report.

2. The simulator can be landed successfully according to the definition given in this report without use of the cockpit instruments.

3. The simulator can be landed with a mean sink rate of 2 ft/sec provided the pilot retards the throttles after touchdown and has been thoroughly familiarized with the simulation.

4. Changing the aircraft dynamic response has a much greater effect upon the pilot's landing performance than turning off the motion system.

B. Recommendations

It is recommended that:

1. An investigation be conducted to investigate further performance when the throttles are retarded after touchdown. This investigation should consider engine thrust response, visual display height cues, and whether this phenomena of reduced sink rates can be repeated using other pilots.

2. Experiments be conducted to determine learning curves for landing simulations for other pilots.

3. Experiments be conducted to determine the effect of varying cues upon simulation landing performance, and these experiments be correlated with an analysis of human information processing. These experiments should be particularly interested in visual cues and their interaction with other cues such as motion.

4. Inflight data be collected to permit verification of the results found in simulation.

5. A study be conducted to quantitatively determine the differences in pilot behavior when in an aircraft and when in a simulator. This study would be concerned with such measures as instrument scan patterns.

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